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FAILURE ANALYSIS OF AN 84-MM, M3, CARL GUSTAF, RECOILLESS RIFLE

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13. ABSTRACT (Maximum 200 words)
During a February 26, 1997 training exercise at Fort Benning, Georgia, an 84-mm, M3, Carl Gustaf, shoulder-fired, recoilless rifle—the TACOM-ARDEC Multi-Role, Anti-Armor, Anti-Personnel Weapon System (MAAWS)—failed while firing an FFV552 training round. The composite-wrapped, steel-lined barrel burst open beneath the trigger housing—destroying the weapon but leaving the Gunner and Assistant Gunner uninjured. The rifle (serial number 14051) was evaluated in the field and at Benet Laboratories. Inspections included a bore surface inspection, dimensional checks, a magnetic particle inspection, an ultrasonic inspection, a crack evaluation, and a bore debris analysis. Although there is no clear evidence regarding the cause of the failure, the evidence does indicate that the failure may have been caused by a soil obstruction in the barrel. This obstruction probably produced a large amount of highly localized stress on the carbon fiber, composite-overwrapped, steel barrel—thereby causing the jacket that contains the pressure to fail and allowing the pressurized propellant gases to deform and rupture the underlying steel liner.

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INTRODUCTION

On February 26, 1997, a catastrophic failure of an M3, Carl Gustaf, 84-mm recoilless rifle occurred during a training exercise being conducted by the Third Battalion of the Seventy-fifth Ranger Regiment at Fort Benning, Georgia. The barrel under the trigger housing ruptured—severing the carbon/epoxy composite laminate jacket and splitting the underlying steel liner along a rifling groove. Fortunately, the Gunner and the Assistant Gunner were not injured.

The M3 rifle is a lightweight, shoulder-fired, anti-tank, anti-personnel weapon manufactured by the Swedish company Bofors, Inc. It is used by the U.S. Army's Seventy-fifth Ranger Regiment, the U.S. Navy, and various foreign military services. The M3 can fire multiple shots and a variety of munitions—including anti-tank, high explosive, smoke, illumination, and training rounds. The round fired at the time of the incident was the FFV552 training round.

An initial cursory evaluation of the rifle, an interview with the Gunner and Assistant Gunner, and an inspection of the incident site did not reveal the cause for the rupture. Because a more detailed examination was needed to determine the cause of the failure, the rifle was sent to TACOM-ARDEC Benét Laboratories, where a series of inspections was performed. This preliminary report describes these inspections in detail. A final report will be issued at a later date.

INITIAL INSPECTION

An initial inspection of the M3 rifle revealed that both external and internal surfaces were covered with sand. Some of the hardware was damaged—including the cocking lever and sight bracket. The composite jacket was burst open in a zigzag-shaped crack that was approximately 2.5 inches long and 0.125 inch wide. The crack was centered 12.75 inches from the muzzle in the 4:00 position (looking from the rear of the rifle with 12:00 being at the top), and the liner bulged outward into the failed area. This bulge was roughly heart-shaped, and a crack ran longitudinally down the middle of it. An evaluation with an optical borescope revealed that sand was packed into the crack on the liner. Bore scratches and other abnormal features were not evident.

The rifle firing record indicated that the weapon had fired a total of 354 rounds at the time of the incident. The M3 rifle currently has a safe service fatigue life of 500 rounds. A complete inspection of the rifle had been conducted on February 5, 1997—when the total round count was 313 rounds—and included a bore dimensional check, a magnetic particle crack inspection of the liner, and an ultrasonic inspection of the composite laminate. No deficiencies were found during that inspection.

The incident site was the Left Coolage firing range at Fort Benning, Georgia. The Gunner was firing in a standing position behind a sand berm. The ground was hard-packed sand, with a clear area behind for a blast zone.

GUNNER INTERVIEW

An interview with the Gunner and Assistant Gunner revealed the following information. The incident occurred at night in calm, mild conditions. The rifle was clean, and a safety check was performed prior to firing. Four rounds were fired in succession, with the failure occurring on the fourth round. The first round was a high explosive round; the second was a smoke round; and the third and fourth rounds were training rounds (*i.e.*, FFV552). The first three rounds were successfully fired, with no unusual events. However, the Assistant Gunner reported that he was unable to insert the second training round completely into the barrel during loading. He subsequently removed the round, ensured that no foreign material was on it, and reached into the rear of the barrel (approximately 55 to 60 cm) to check for an obstruction. No obstruction was found. The round was then successfully reinserted and fired.

The Gunner noticed that the flash signature was brighter than normal, with a perceived increase in launch duration. The round appeared to corkscrew toward the left and emitted a high pitched, whining noise until it hit the ground 100 to 200 meters away (the aim point was 400 to 500 meters). The rocket motor on the projectile was operating during the flight. A significant forecoil of the rifle pulled the Gunner over the sand berm he was standing behind—causing the rifle's muzzle to dig into the sand. The fire control assembly and sight separated and went down range approximately 3 to 6 meters.

LABORATORY TESTS

The rifle was shipped to Benét Laboratories so the damage could be documented and the cause determined. Measurements and inspections were performed to determine the cause of failure, and the material conditions were documented as fully as possible for possible reanalysis at a later time.

Video Bore Mapping

Looking into the venturi from the breech end, a substance similar to sand was seen. This substance covered about two-thirds of the venturi's bore and was also visible on the tube itself. Oxidation that looked like rust was also visible on the tube. A narrow band of liner dilation was seen two-thirds of the way down the bore in the tube (closer to the muzzle end).

A full bore inspection was performed and recorded using an Olympus fiber-optic borescope with an attached video camera, monitor, and recorder. Several significant observations were made. A drag mark was found 19.4 inches from the breech end of the tube in the same groove as the failure fracture; several other drag marks were found in the same general position. Most of these marks ended abruptly at the dilation area, although some turned into scrapes that ended as grooves with a chip of steel liner material at the dilation area. A large amount of sand coated the entire bore and venturi surface. This was most likely the result of the rifle being pushed into the sand after the barrel failure. When the prefiring position of the FFV552 round

was compared to the well-defined origin of the scrape marks, it was found that the front bore rider on the projectile was located approximately 2.5 inches away from the origin of the marks at the rear of the barrel. Table 1 lists the major points of interest and their location.

Table 1. Points of Interest Identified During Video Bore Mapping

	Distance from Muzzle	Distance from Breech	O'clock Position	Distance from Rear Face Venturi
Beginning of drag mark	14.1"	19.4"	4:00	27.9"
Beginning of fracture	12.7"	20.8"	4:00	29.3"
Object in fracture	11.5"	22.0"	4:00	30.5"
Muzzle end of fracture	10.6"	22.9"	4:00	31.4"
Dilation in bore	10" to 13"	20.5" to 23.5"	1:00 to 8:00	20.5" to 23.5"
Breech end of composite separation	12.75"	20.75"	4:00	
Muzzle end of composite separation	10.5"	23.0"	4:00	
Length of weapon with venturi attached: 42"				
Length of tube alone: 33.5"				

External Damage Evaluation

The tube (serial number 14051) and the attached venturi (serial number 14046) were visually inspected for damage, and the following observations were made. The tube and venturi were connected via a venturi axis pin. The following items were missing:

- front grip and projection
- rear sights and projection
- keyways for telescopic sight support bracket
- muzzle end dovetail slots for firing mechanism
- most of the firing mechanism tube (only the portion of the tube from the rear attachment location to the breech firing pin housing remained)
- firing rod and main spring
- trigger/handle assembly and dovetail projection
- shoulder pad and sling

The outside surface of the rifle was photographed to document laminate damage; Figure 1 shows the extent of that damage. The laminate was severed under the trigger housing—detaching it and the adjacent hardware from the barrel. The laminate failure crack is jagged, which is typical for a carbon-reinforced plastic composite, and is approximately 2.5 inches long. The

rough appearance around the cut was caused by the failure of the adhesive bond that holds the trigger housing base to the barrel. No other damage to the laminate was found.

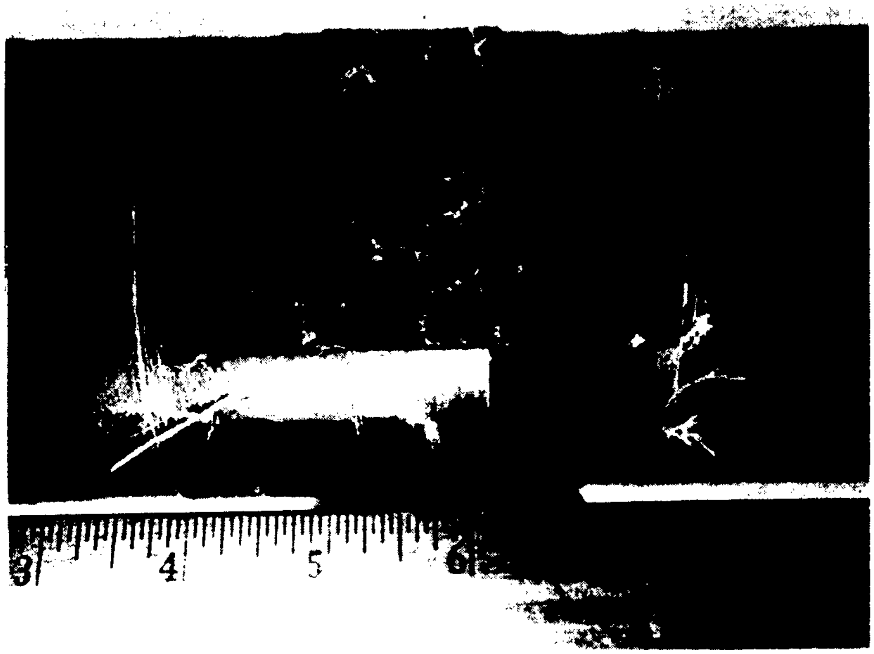

Figure 1. External photograph of failed composite laminate

External Dimensions

Where possible, the outside dimensions were measured in the 12:00/6:00 and 3:00/9:00 planes using a standard caliper. These results are shown in Table 2. With the exception of the damaged area, the dimensions were normal.

Bore Dimensions

Using a two-point star gage, the bore diameters were measured at two-inch increments at both the 12:00/6:00 and 3:00/9:00 planes. The results are shown in Tables 3 and 4. The bore diameters are clearly enlarged in the failed area where the liner bulges outward. Table 4 also includes the bore dimensions recorded during the February 5, 1997 rifle inspection. When compared to the earlier inspection, the barrel does not have a larger internal diameter toward the breech end of the crack—indicating that the barrel did not experience a plastic deformation of the liner and a residual expansion in this area. Toward the muzzle end of the crack, the bore diameters are slightly larger, which may be attributable to post-failure projectile dynamics because the internal pressure would have already been vented through the failed liner and would not have deformed the barrel. These data support the supposition that an excessive pressure event did not occur.

Table 2. Ultrasonic Inspection Results

O'clock Position	Distance from Muzzle	Findings
12:00	Full length of tube	Normal bore echo (no delaminations found)
1:00	10" to 11.5"	Delamination found between third and fourth layers
2:00	11"	Delamination found between first and second layers
3:00	12.5" to 13"	Delamination found between second and third layers
3:00	10.5" to 11.5"	Delamination found between second and third layers
4:00	9.25" to 9.75"	Delamination found between second and third layers
4:00	8.5" to 9"	Delamination found between first and second layers
4:00	9.75" to 13.25"	Visible break in composite layer #4
4:00	11" to 12.5"	Can see white layer between third and fourth layers
5:00	10.25" to 13.25"	Visible separation
6:00	9.5" to 10.5"	Delamination found between first and second layers
7:00	8.5" to 9"	Delamination found between first and second layers
8:00	10.75" to 13"	Delamination found between second and third layers
9:00	13" to 13.25"	Delamination found between third and fourth layers
9:00	9" to 10.5"	Delamination found between second and third layers
10:00	12.75" to 13.25"	Delamination found between third and fourth layers
10:00	9" to 10.5"	Delamination found between third and fourth layers
11:00	Full length of tube	Normal bore echo (no delaminations found)

Table 3. External Diameters

Location (From Muzzle)	12:00/6:00 Plane	3:00/9:00 Plane
2"	3.729"	Hardware
4"	3.729"	3.749"
6"	3.756"	3.744"
8"	3.931"	3.959"
10"	3.964"	3.966"
12"	3.991"	3.972"
14"	3.953"	3.955"
16"	3.995"	3.991"
18"	N/A	4.028"
20"	N/A	4.028"
22"	N/A	4.051"
24"	N/A	4.070"
26"	N/A	4.060"
28"	N/A	4.087"

Table 4. Bore Diameters from Star Gage Inspection (Land to Land)

Location from Muzzle	12:00/6:00 Plane	3:00/9:00 Plane	Sizes from 2/5/97 Inspection 12:00/6:00	Sizes from 2/5/97 Inspection 3:00/9:00
23"	3.307	3.308	3.308	3.309
21"	3.307	3.308	3.310	3.309
19"	3.307	3.308	3.310	3.309
17"	3.309	3.307	3.311	3.310
15"	3.312	3.306	3.311	3.309
13"	3.318	3.299	3.311	3.309
12"	3.364	3.321	N/A	N/A
11.75"	3.373	3.322	N/A	N/A
11.5"	3.369	3.321	N/A	N/A
11.25"	3.367	3.317	N/A	N/A
11"	3.351	3.313	3.310	3.309
10.75"	3.332	3.308	N/A	N/A
10.5"	3.322	3.307	N/A	N/A
10.25"	3.317	3.305	N/A	N/A
10"	3.314	3.304	N/A	N/A
9.75"	3.313	3.304	N/A	N/A
9"	3.312	3.304	3.310	3.309
8"	3.311	3.305	N/A	N/A
7"	3.314	3.305	3.309	N/A
5"	3.315	3.293	3.309	N/A
3"	3.313	3.301	3.309	N/A
1"	3.307	3.307	3.310	N/A

<u>Ultrasonic Inspection</u>

An ultrasonic inspection of the composite laminate was performed to check for delaminations and other anomalies. During this inspection, sound waves are sent into the composite material from the outside surface, and reflected echos are observed and interpreted. This inspection was performed using a Krautkramer ultrasonic unit (model USIP-11) with an Aerotech 10 Mhz normal beam probe. Irregular delaminations that were stepwise in nature were found in the areas immediately surrounding the composite failure. This was expected in the areas so close to the damage. Other areas of the barrel had no indications of delamination or other composite damage. The results of the inspection, which are shown in Table 2, are listed relative to the o'clock position, distance from the muzzle end of the tube, and the composite layers affected. The composite jacket is composed of four discrete layers of carbon/epoxy, hoop-wrapped material that are separated by layers of axial glass/epoxy material. The layers in the table refer to the four different carbon/epoxy layers.

Barrel Cutting

The barrel was cut into several sections, as shown in Figure 2. A 16.125-inch long, breech fatigue specimen was cut from the barrel for possible use in the Multi-Role, Anti-Armor, Anti-personnel Weapon System (MAAWS) Gun Life Study. The section from the muzzle to a distance of 8 inches into the barrel was also sectioned off and set aside. The failure zone, which included 8 inches from the muzzle point to a distance of 16.5 inches from the muzzle, was removed and cut in half lengthwise (from 1:00 to 7:00) to expose the liner crack for analysis. The small remaining section was polished on one side and used to measure liner thickness and evaluate laminate and liner quality. Before cutting, a piece of tape was placed over the liner crack on the bore surface to capture any debris that may have fallen out during the cutting operation.

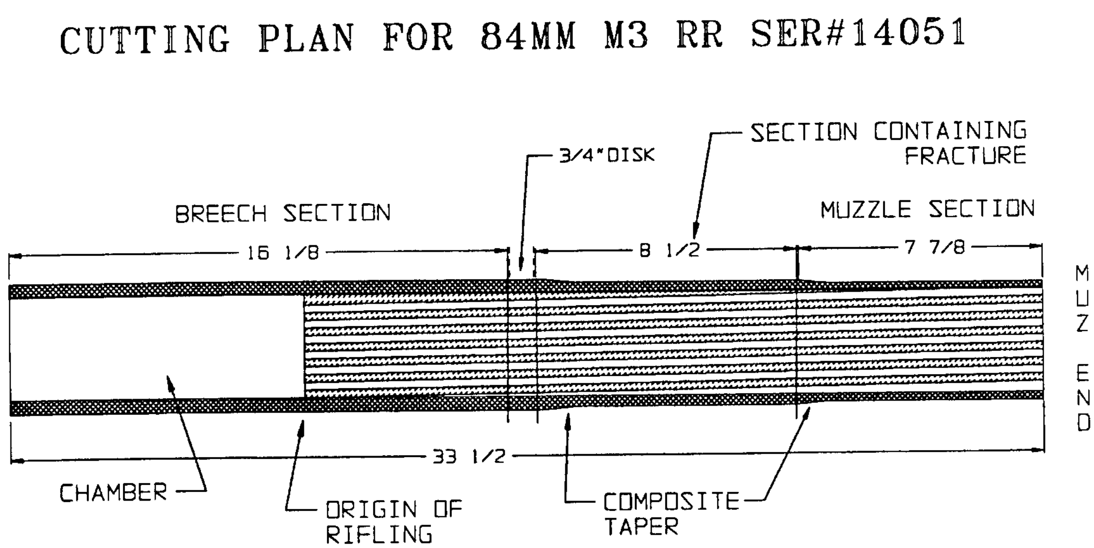

Figure 2. Barrel specimen cut location sketch

Crack and Bore Surface Debris Analysis

Debris that was found on the bore surface and in the liner crack was analyzed via a spectrum analysis, which showed high levels of silicon material. This material was the sand and soil particles that were introduced into the barrel before and during the incident. The material in the liner crack was a mixture of sand and soil; it extended into and along the liner/composite interface. This material was probably forced into this area by the projectile and/or propellant gases—not by simple saturation of the area by soil after the rifle muzzle dug into the sand berm. Additional details concerning the chemical composition and physical microscopic appearance of this debris will be contained in the final technical report.

Liner Thickness Examination

The ring section that remained after the rifle was cut into sections was polished on one side and evaluated under an optical microscope in order to measure the liner's thickness in several o'clock positions. Similar measurements taken from ring specimens on other MAAWS rifles revealed large deviations in thickness. However, the effect that a low wall thickness may have on the pressure containment capability of the rifle is negligible because a cracked liner may allow propellant gases to impinge on the inner surface of the composite jacket—thereby lowering its strength.

The liner wall thicknesses of individual grooves at the 12, 3, 6, and 9 o'clock positions were optically measured on tube #14051. Three grooves at each position were measured—one at the exact o'clock position and one to either side of the initial measurement. These measurements were designated as C (center), R (right of center), and L (left of center). All measurements were taken at a magnification of 100x, and the results are reported in millimeters. The results are provided in Table 5.

Table 5. Liner Thickness Evaluation Results

O'clock Position											
12:00			3:00			6:00			9:00		
L	C	R	L	C	R	L	C	R	L	C	R
0.53	0.45	0.46	0.49	0.55	0.57	0.64	0.64	0.64	0.62	0.62	0.60

The thickness measurements show that the liner is at or above the minimum thickness tolerance of 0.45mm. The composite wrap was also examined along the circumference of the tube section, and it appeared to be of the same high quality laminate found on other MAAWS barrel sections.

Bore Surface Examination

After the rifle barrel was cut open, the exposed bore surface was evaluated using optical stereo microscopy and laser scanning confocal microscopy. Figure 3 shows the failed liner section with the deformed liner and crack. Although debris is seen on both the surface and in the crack, most of the debris in the crack was ejected during the cutting process.

Figure 4 is a close-up image of the liner near the crack; the image shows several gouge and scrape marks on both the lands and grooves. A stereomicroscope clearly indicates that these marks were the result of ductile abrasion with a hard substance; the steel liner material is "walled up" in several locations. Debris is more easily identifiable in this figure.

Figure 5 contains a more detailed image of a single rifle groove. Grooves and intermittent gouging are clearly seen on the surface. A large amount of debris is also shown in the rifling groove that extends up onto the land. Figure 6 shows an extreme close-up of the termination of a gouged out groove. In this image, it is obvious that small particles caused the surface damage because the high hardness sand particles in the soil can leave this exact signature. Figure 7 shows how a particle of sand can leave marks that are similar to those seen on the liner surface. Figure 8 shows what happens when an abrasive particle is rolled over a surface and trapped between two layers. The signature is a series of short grooves and gouges (labeled as A). An abrasive particle can also be dragged along the surface (as shown in signatures B and C). Both of these signatures are found on the liner surface near the failure zone at the breech end. This evidence—along with the debris found in the crack and elsewhere in the barrel—proves that soil was in the barrel before firing and helped to damage the liner surface and possibly fail the barrel.

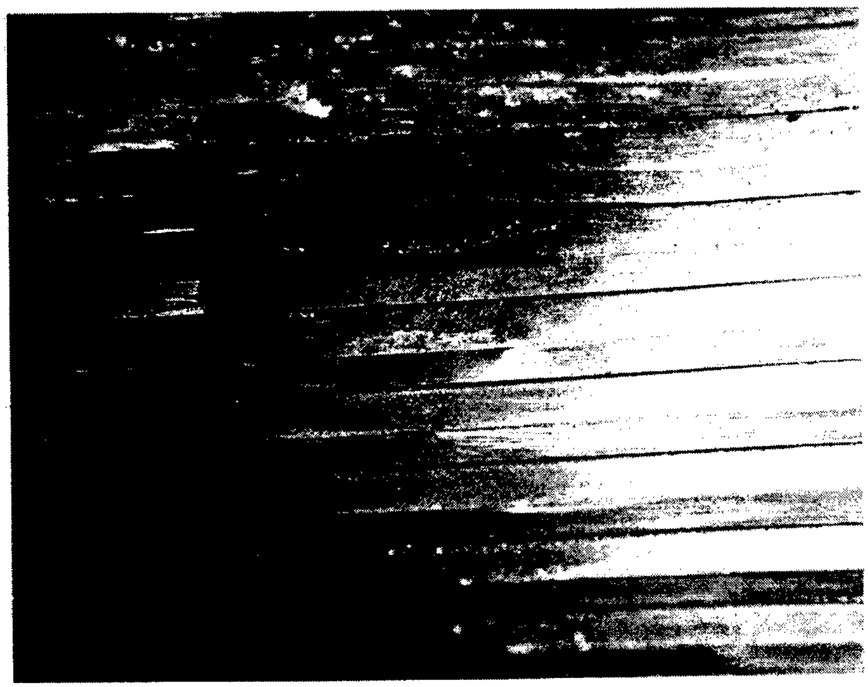

Figure 3. Liner crack and deformed area (0X)

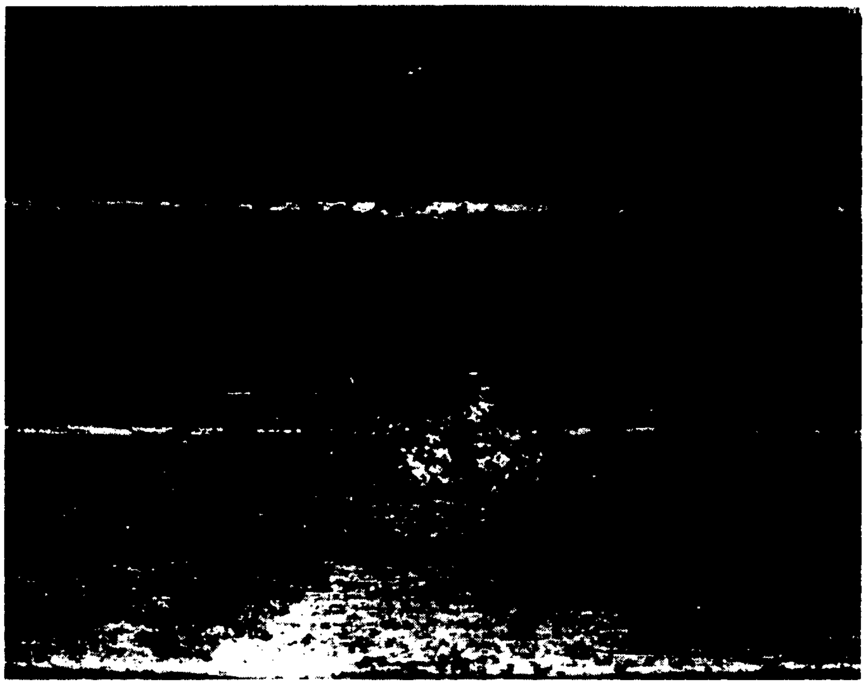

Figure 4. Gouge and scrape marks on liner near failure crack (2.7X)

Figure 5. Close-up of groove with grooves and intermittent gouges (7.2X)

Figure 6. Laser confocal image of termination of a groove (200X)

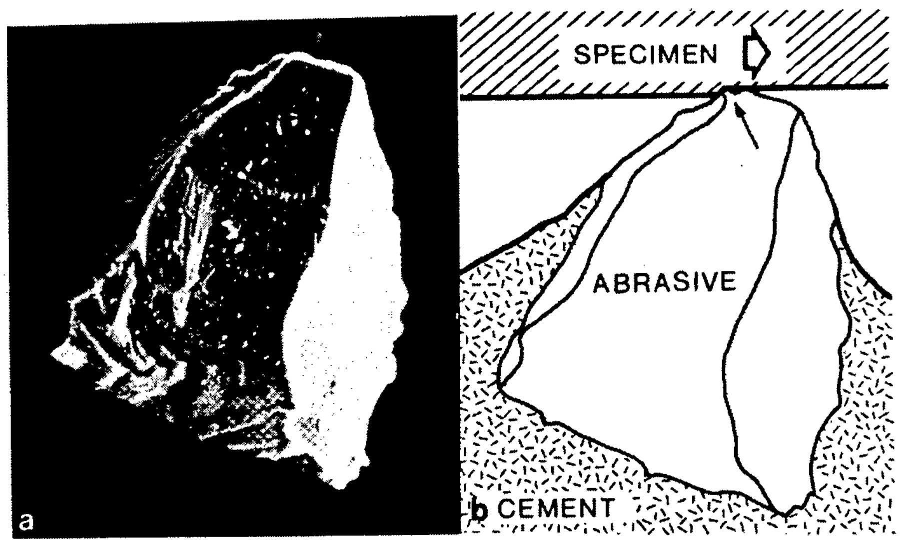

Figure 7. Photograph and action of an abrasive particle on a surface (ref 1)

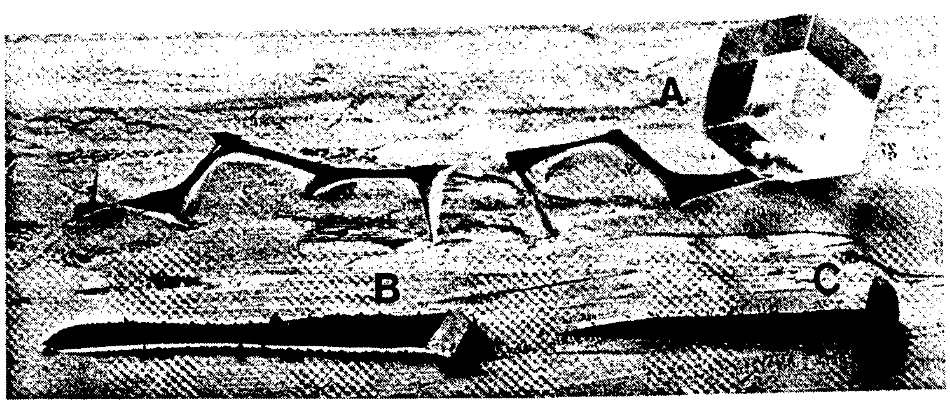

Figure 8. Surface marks caused by the action of an abrasive particle (ref 1)

Magnetic Particle Inspection of Liner

A magnetic particle inspection of the liner was performed to locate any additional cracks. To prevent the contamination of surface evidence by the "Magnaglo" solution application process, this inspection was done after the rifle had been cut into three sections and the surface evaluation had been performed. The steel liner was magnetized by a portable electromagnet (Magnaflux type Y-5, 6 amps), sprayed with a "Magnaglo" solution, and examined under a black light (Magnaflux Model ZB-100F, 2 amps) and an Olympus Fiberoptic Scope. No cracks other than the large failure crack were found. This procedure was also used during the earlier field inspection of rifle #14051; no cracks were found at that time, nor were any cracks found in any of the M3 rifles during field inspection. However, this technique found cracks in the failed hydraulically cycled sections in the MAAWS Gun Life Study, which means that significant cracks could be found if present.

Crack Examination

To expose the crack surface for further evaluation, the portion of the liner containing the crack was separated into two components. Figure 9 shows the crack surface. No fatigue striations were evident—indicating that the failure occurred in a single cycle. A large shear lip was also found. Taken with the lack of striations, this clearly indicates that the liner failed in a single cycle ductile failure.

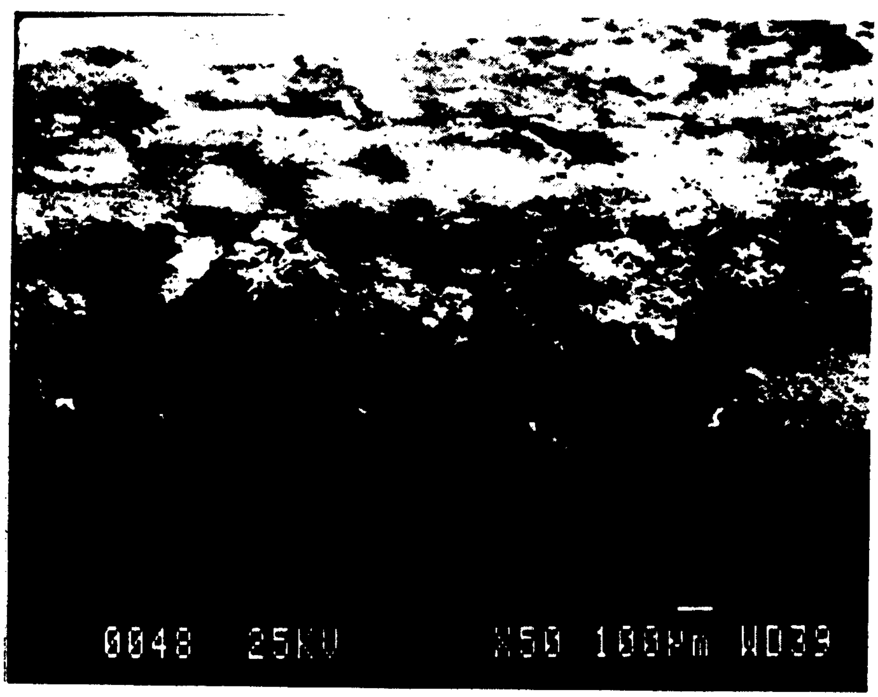

Figure 9. Scanning electron microscope image of liner failure crack surface

ANALYTICAL AND EXPERIMENTAL FAILURE ANALYSIS

The composite barrel was analyzed to determine at which pressure it is expected to catastrophically fail in the area of the actual burst. This knowledge helps to determine the available margin of safety when firing the rifle at maximum pressure. An internal ballistic analysis model coupled with a structural analysis model is highly desired because this combination allows for analyses of firing with obstructions, excessive propellant, pinched barrels, and so forth. However, although the required analytical and numerical tools are available, they require modifications that are beyond the time and economical limits of this investigation.

The rifle is a hybrid structure that consists of a thin steel liner wrapped with a relatively thick layer of low modulus, moderate strength, carbon fiber epoxy matrix composite material. The carbon fibers have a high angle of wrap that is in a circumferential or hoop direction, which aligns the fibers with the principal stress direction generated by the firing pressure load. The glass fibers are aligned with the rifle's longitudinal axis to provide longitudinal strength.

A multi-layered orthotropic cylinder analysis (ref 2) was used to calculate the pressure required to burst the different sections of the rifle. The material properties used were as follows.

Liner inside diameter (grooves):	3.386"
Liner outside diameter:	3.425"
Liner material:	Steel, yield strength = 113 Ksi
Jacket material:	Carbon/epoxy, strength = 210 Ksi
	Modulus of elasticity = 20 Msi

For the zone that failed, the stress level in the inner layer of composite material reached its maximum strength level at a pressure of 28,200 psi. At this loading, the strain at the bore of the liner was 1.11%. Actual hydraulic bursting of the barrel's ring sections from the zone in question were performed at Benét Laboratories as part of the MAAWS Rifle Gun Life Study. Two undamaged sections were burst at 19,541 psi and 20,771 psi. Obviously, a large discrepancy exists between the actual and calculated values; this means the analytical model and input data must be evaluated more closely. Possible improvements would be to allow for liner plastic deformation and a lower load transfer between layers of the carbon/epoxy wrap. In any case, the pressure required to hydrostatically burst the rifle barrel in the section under investigation is quite large—much larger than the firing pressure generated in that section, which is estimated to be less than 5,000 psi. Because the failure pressure is so much higher than the maximum working pressure, a failure caused by overpressurization is considered to be very unlikely.

CONCLUSIONS

After evaluating the physical evidence and the Gunner's testimony, it is highly probable that a soil obstruction caused the barrel failure. Soil debris was found in the barrel, packed inside the liner failure crack, and in between the liner/jacket interface. Abrasive particle gouging and

grooving found on the liner surface up to the failure point show that hard soil sand particles were present during the failure or a previous firing event. This soil obstruction could have been picked up by the rifle's muzzle (unknown to the Gunner), or it may have been introduced into the rifle by the projectile.

Early ignition or detonation of the projectile rocket motor can be discounted because the rifle's manufacturer states that such an event would not cause a significant pressure increase. In addition, the rocket motor was operating during the projectile flight.

A composite failure is unlikely in light of the large ratio of pressure containment capability to actual working pressure. The laminate was evaluated for defects and damage, and none were found. The rifle's jacket and liner appeared to be no different than any of the other barrels examined as part of the MAAWS Gun Life Study. In addition, no indications of other liner cracks or overexpansion, as evident from the chamber bore dimensions shown in Table 6, were found—even in the vicinity of the failure. This indicates that it was highly localized—similar to the type of failure that an obstruction would cause.

Table 6. Chamber Diameters

Distance from Breech End	12:00/6:00	3:00/9:00
0"	3.489	3.490
2"	3.475	3.475
4"	3.457	3.457
6"	3.436	3.436
8"	3.416	3.415

Although there is no clear evidence to explicitly demonstrate the cause of the failure, the existing evidence strongly supports the notion that the failure was caused by a soil obstruction in the barrel prior to firing. This obstruction is believed to have caused highly localized, high stress in the carbon fiber composite, overwrapped steel barrel—thereby failing the pressure-containing jacket and allowing the pressurized propellant gases to deform and rupture the underlying steel liner.

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1. Samuels, L. E., "Metallographic Polishing by Mechanical Methods," ASM, Materials Park, OH, 1982.

2. Witherell, M. D., "A Plane-Strain Elastic Stress Solution For a Multiorthotropic-Layered Cylinder," ARDEC Technical Report ARCCB-TR-90016, Benét Laboratories, Watervliet, NY, June 1990.

APPENDIX–SCANNING ELECTRON MICROSCOPE AND ENERGY DISPERSIVE X-RAY ANALYSIS

The following figures document the results of the scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis of the subject component. It should also be noted that Benét Laboratories' X-ray analyzer cannot detect light elements such as boron.

1. The rifle bore had debris and particles in and around the 2.5" longitudinally-oriented bore crack. Most of these particles were white and/or cream colored, but some of the debris on the breech side of the crack was red. Particles were removed *in situ* (via plastic tape) from the crack and from the surrounding regions prior to sectioning for SEM/EDX analysis. No chemicals were used in the extraction.

   Particles were also extracted from the venturi. Figure 1 shows these venturi particles to be equiaxed (as opposed to film-like), while EDX Figures 1A and 1B show them to be rich in Si. Figure 1A is consistent with silica, and Figure 1B is consistent with silicate. Silica (SiO_2) occurs widely in nature as sand, diatomite, quartz, flint, etc. Silicates are any of the widely occurring compounds of Si, O, and one or more metals, with or without hydrogen. Typical natural silicates are gem stones (except diamond), beryl, asbestos, clay, talc, feldspar, etc. There are also several types of clays (e.g., hydrated aluminum silicate) that are found in soils in varying percentages. Figure 1B is qualitatively consistent with feldspar (a potassium aluminosilicate). The hardnesses of silica (quartz) and feldspar are 820 and 560 Knoop (100 g load), respectively (ref A-1). If the conversions are correct at this low load, this is approximately 59 and 47 R_c, respectively. Both of these are harder than the metal rifle liner, which is approximately 28 to 32 R_c. The hardness of all types of clay could not be ascertained, but those that were found are softer than silica and/or feldspar. Silica melts at 1986 K—approximately 1000 lower than the reported gas temperatures in the rifle bore. Because they are softer, the melting point of feldspar and clay is probably lower than silica. The melting point of the debris may be important because much of the material found in the bore resembles a smeared film (as opposed to equiaxed particles).

2. Figure 2 shows material that was extracted *in situ* from a portion of the liner crack before sectioning. Figure 2A is an "elemental map" of the same area and shows the extracted particles to be rich in Si. The EDX spectrum from this material (shown in Figure 2B) indicates a strong Al presence. Many extracted particles were equiaxed, but others appeared to be film-like. Figures 3 and 3A show large particles near the crack that were also rich in Al and Si. EDX spectra from equiaxed particles were always rich in Si and/or Al.

   Figures 4 through 4D are from particles that were extracted from the liner on the breech side of the crack. This area displayed a reddish appearance. Figure 4 shows a land/groove junction, while Figures 4A and 4B are Si and Fe maps, respectively, from this same area. The pictures show that large, equiaxed, Si-rich particles were concentrated in the

land/groove junction, while finer, thinner, Fe-rich material was present on the land. EDX spectra (shown in Figures 4C and 4D) indicate that the large particles are consistent with silica; the finer particles are probably iron oxide.

3. The cracks on the composite outer diameter and the liner inner diameter were protected with plastic tape while the liner crack was cut to fit into the SEM. (During this cutting, the composite delaminated from the liner.) Figures 5 and 5A show a portion of the liner crack after sectioning. Figure 5 shows debris *in* the crack, while Figure 5A shows the debris to be rich in Si. The crack showed no evidence of brittle fracture.

4. The crack was then "broken open." Figure 6 shows a typical fracture surface (F), with debris still covering much of the separation. This debris was consistent with silica (Figure 6A). The debris was removed via tape to reveal the fracture mode. Figure 7 shows a typical fracture surface (F), while higher magnification (Figure 8) shows the fracture mode to be shear, which is consistent with a single cycle, tensile overload.

5. Figures 9 and 9A show a portion of the crack in the composite, at what had been the composite/liner interface. The elemental map in Figure 9A and the EDX in Figure 9B reveal Si-rich material in and around the crack. EDX analysis of the particle-free composite showed only material consistent with the composite.

6. EDX spectra from interior cut surfaces of a rotating band (Figure 10) showed only F and C, which is consistent with teflon (PTFE).

7. These results show that a large amount of foreign material was present on the inner diameter of the rifle bore. In addition to being deposited on the bore surface, this material was also embedded in the bore crack—to the extent that it completely penetrated through the crack to the composite. This suggests that a large amount of foreign material was present before and during the firing of the last round—the action of which forced the material into the growing crack. At a minimum, the presence of this foreign material was probably a contributing factor to this failure. EDX spectra from this material were consistent with clay, silica, and/or feldspar but do not provide a positive identification. However, it appears that—unless another source of an Si-rich substance is identified—this foreign material most probably represents area soil. A site soil sample should be evaluated.

REFERENCE

A.1. *CRC Handbook of Chemistry and Physics,* 76th Edition, David R. Lide, Editor, 1995-1996.

FIG.#1 **100X**

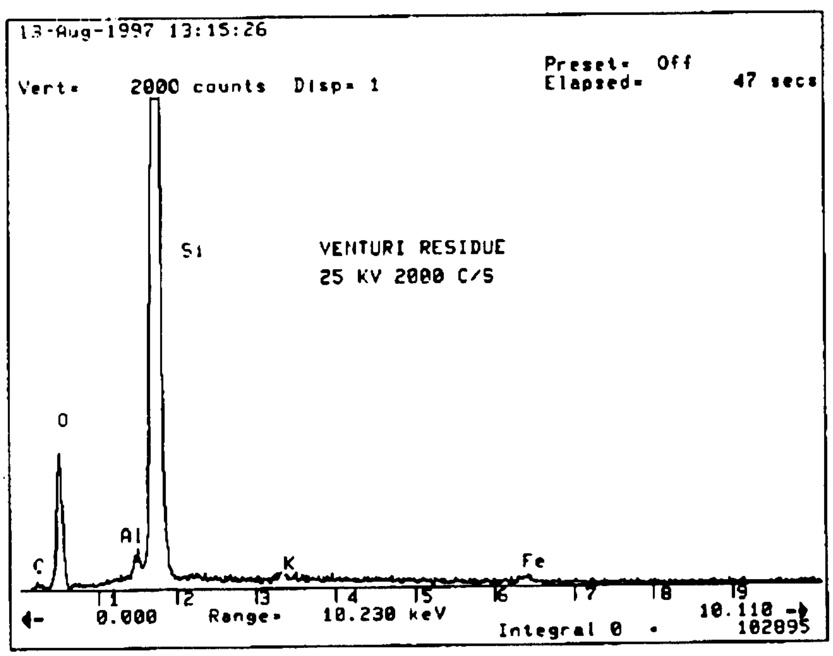


FIG.#1A **EDX**

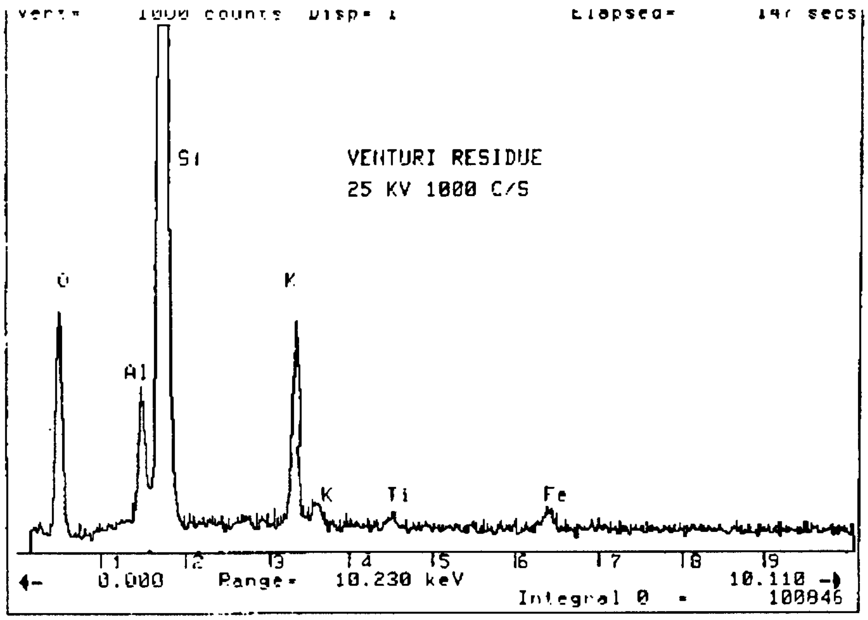


FIG.#1B **EDX**

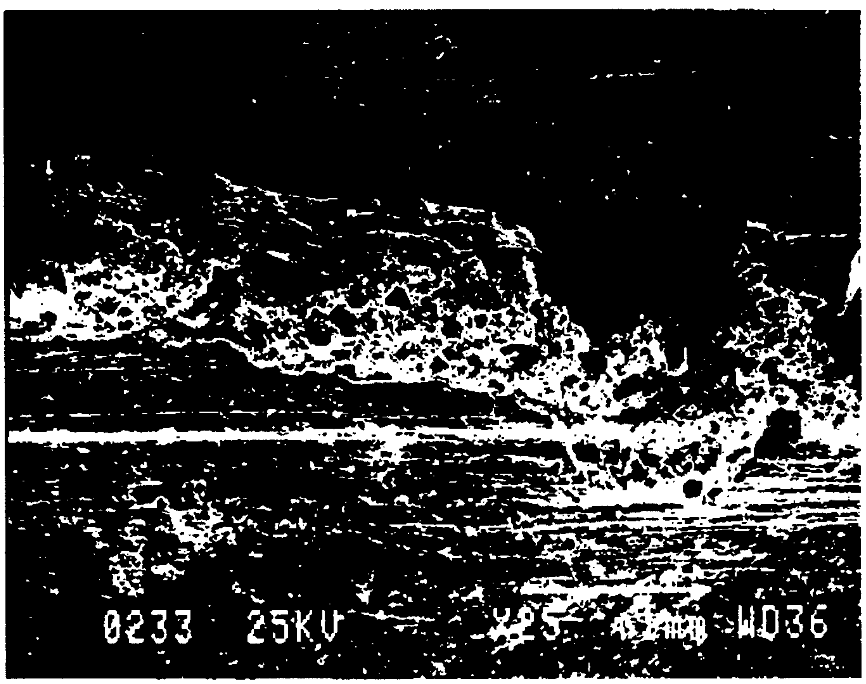


FIG.#2 **25X**

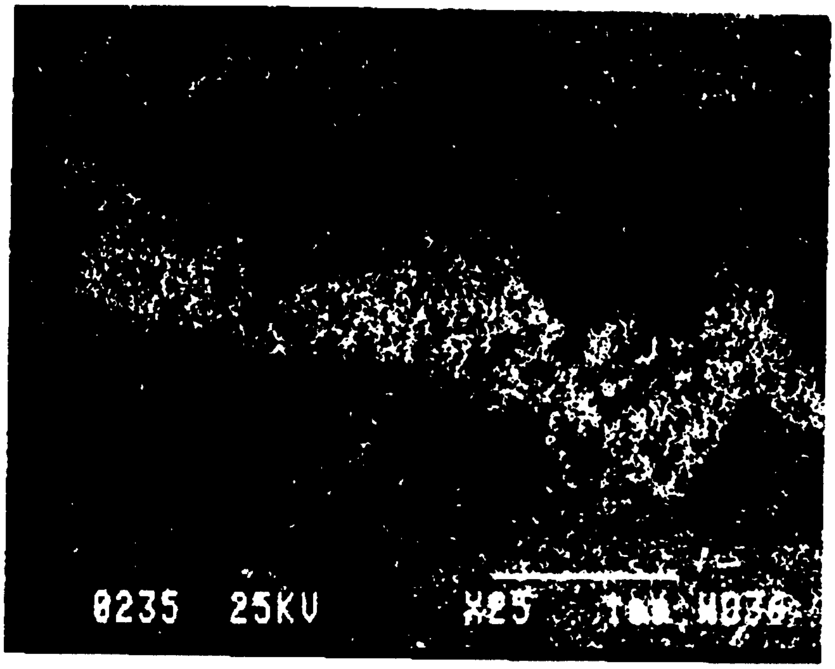


FIG.#2A **Si MAP** **25X**

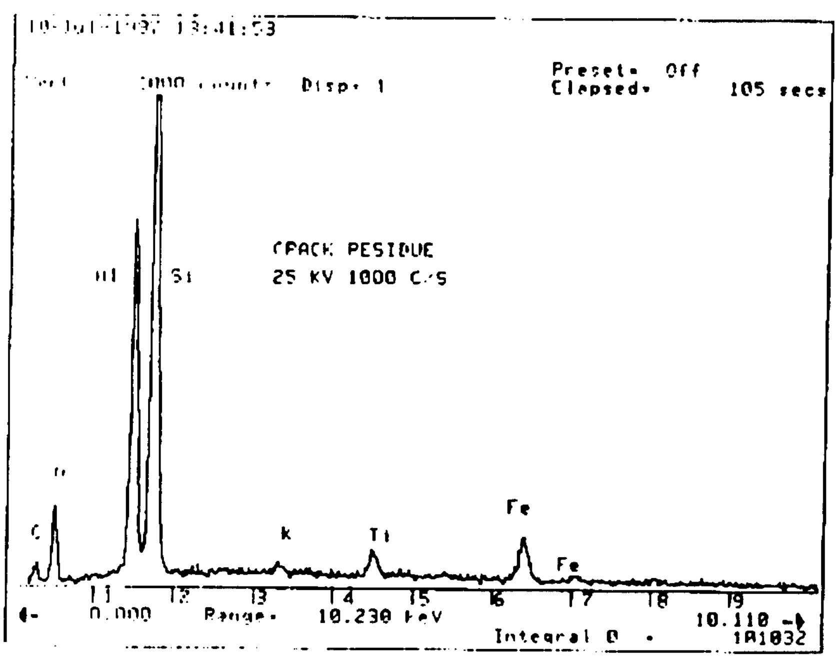


FIG.#2B **EDX**

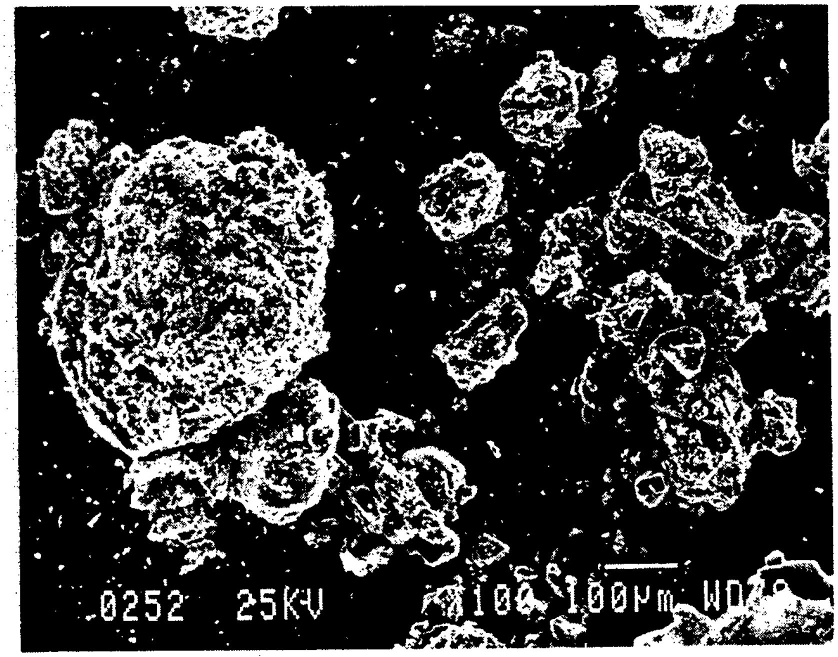


FIG.#3 **100X**

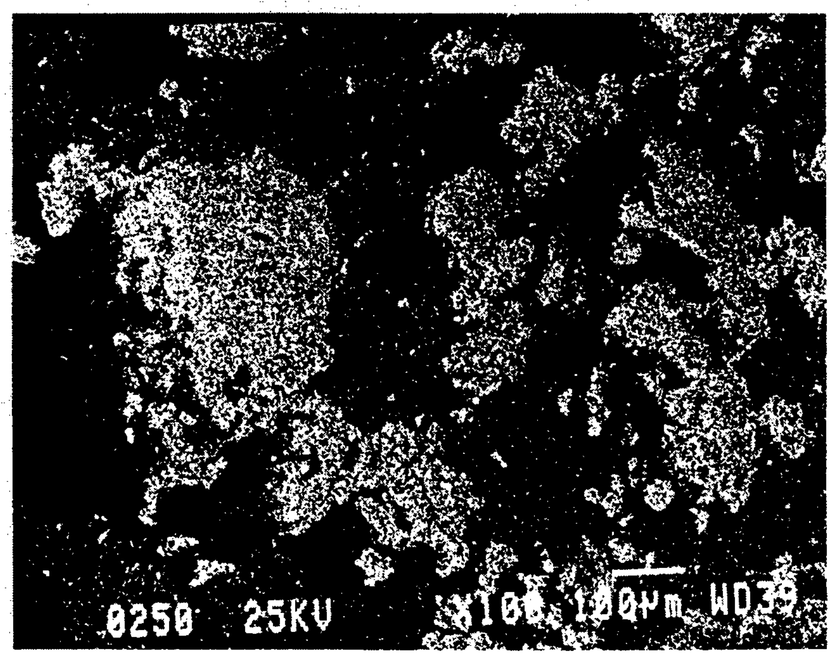


FIG.#3A **Si MAP** **100X**

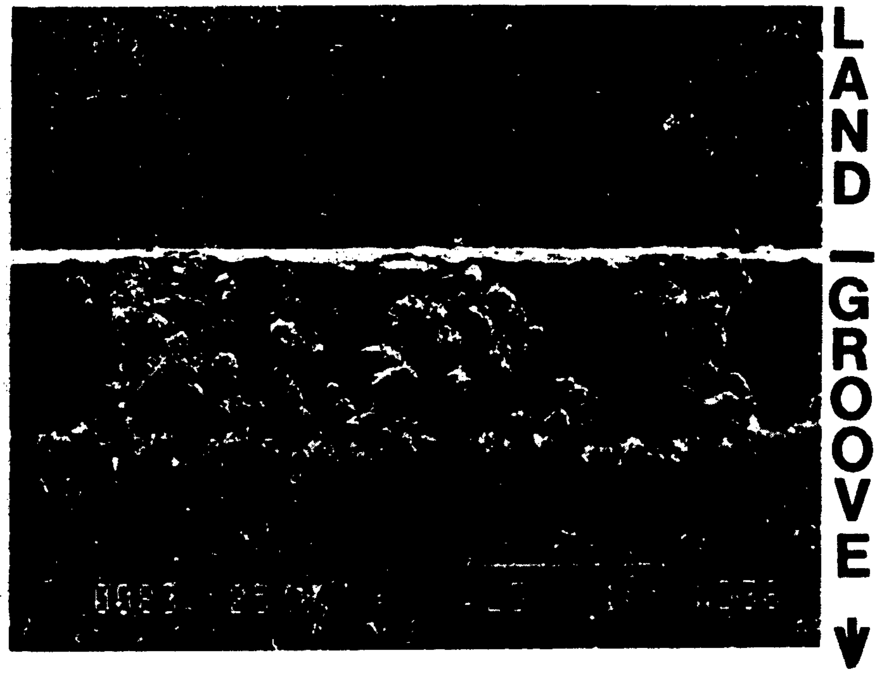


FIG.#4 25X

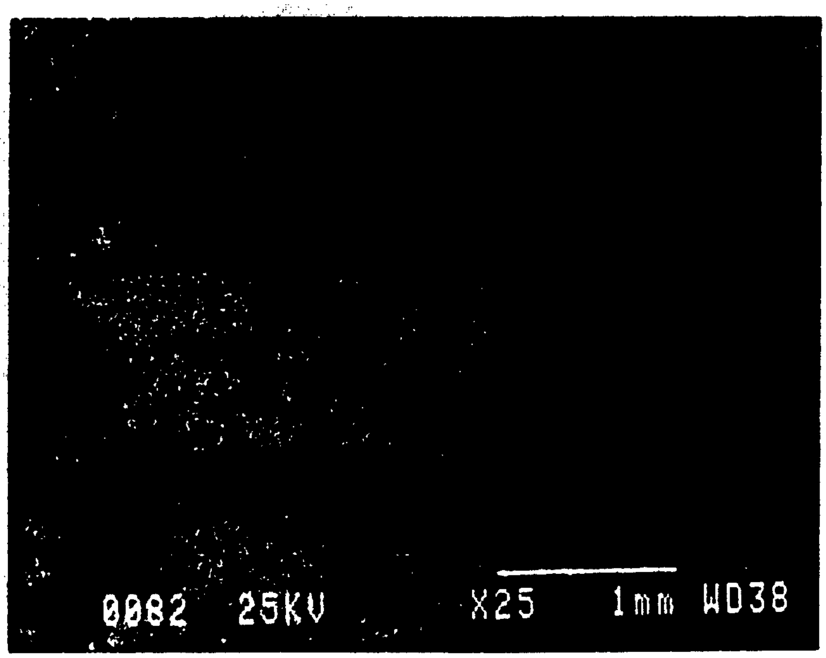


FIG.#4A **Si MAP** **25X**

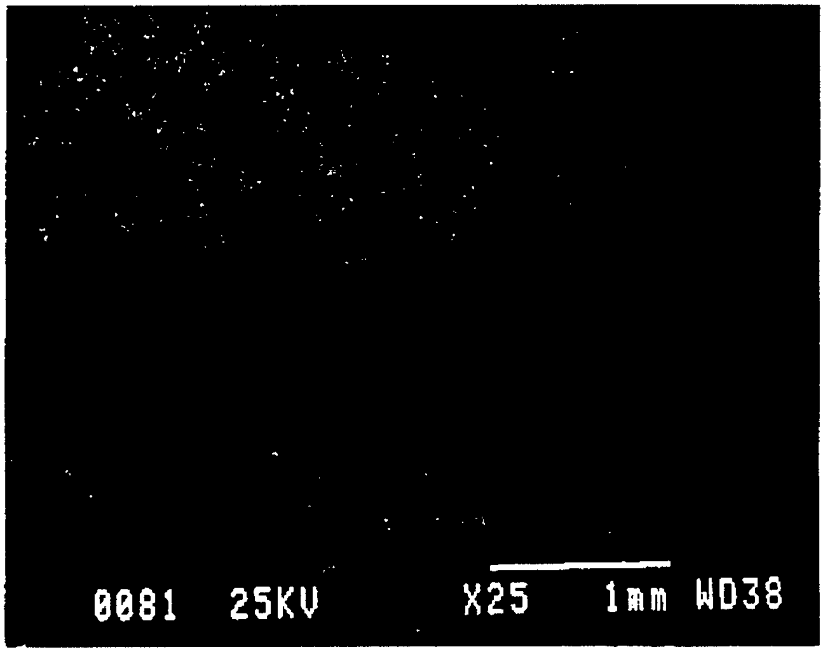


FIG.#4B **Fe MAP** **25X**

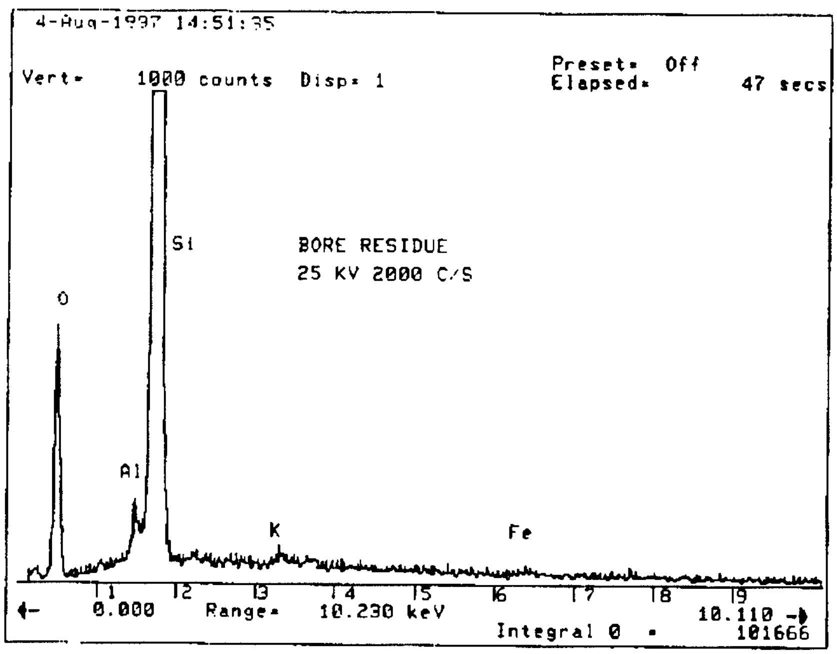


FIG.#4C **EDX**

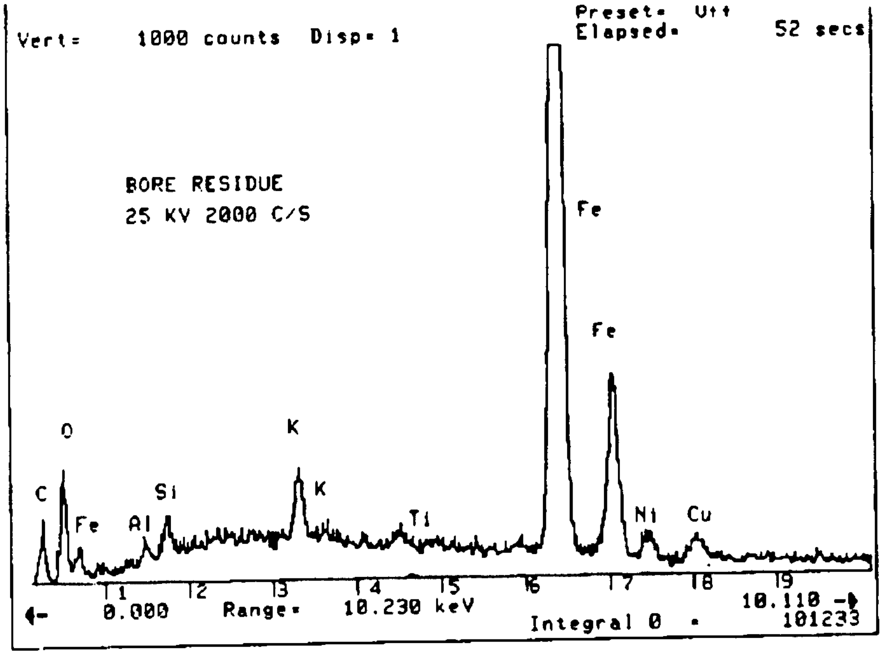


FIG.#4D **EDX**

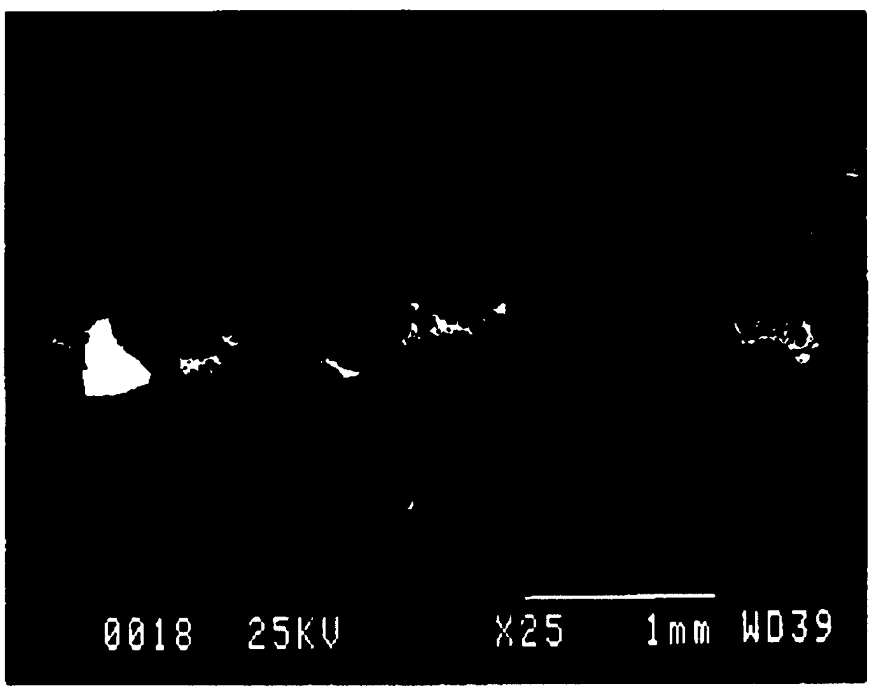


FIG.#5 **25X**

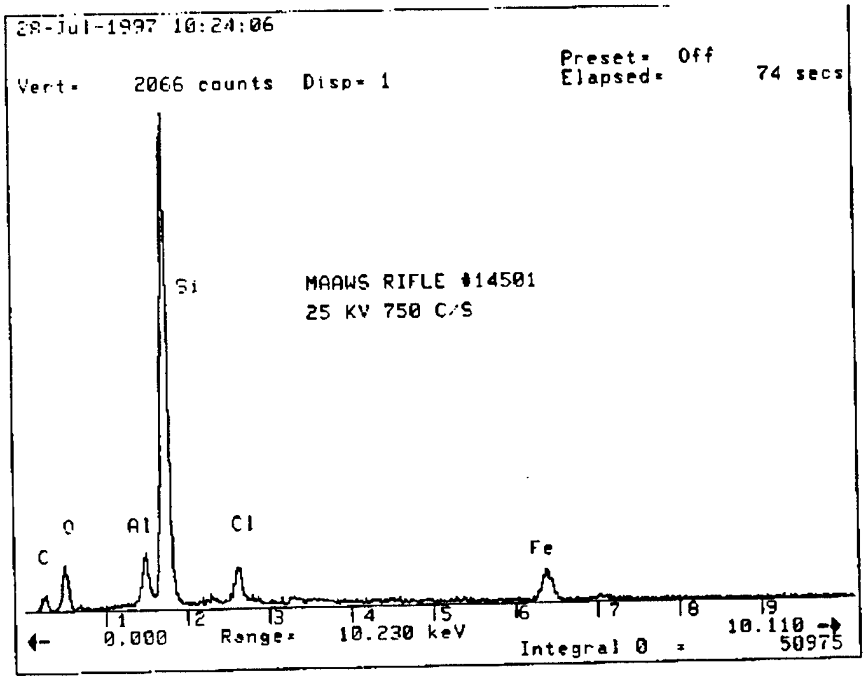


FIG.#5A EDX

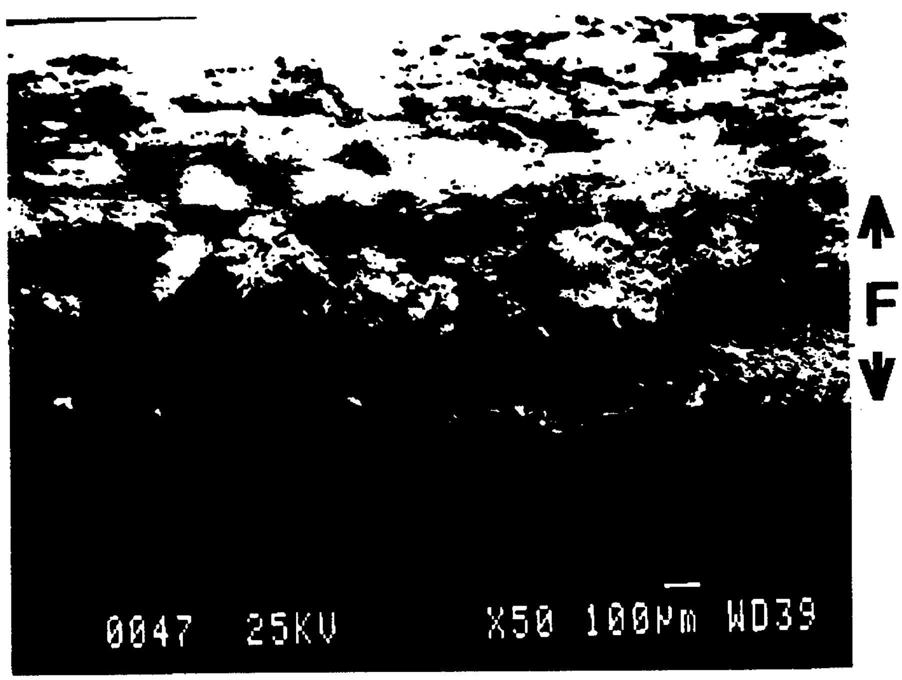


FIG.#6 50X

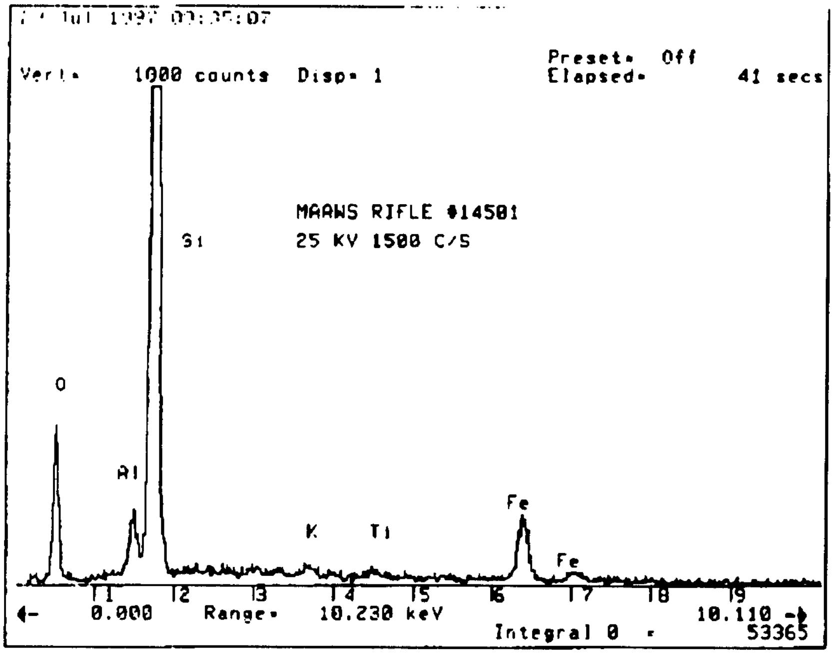


FIG. #6A **EDX**

FIG. #7 **100X**

FIG. #8 **1000X**

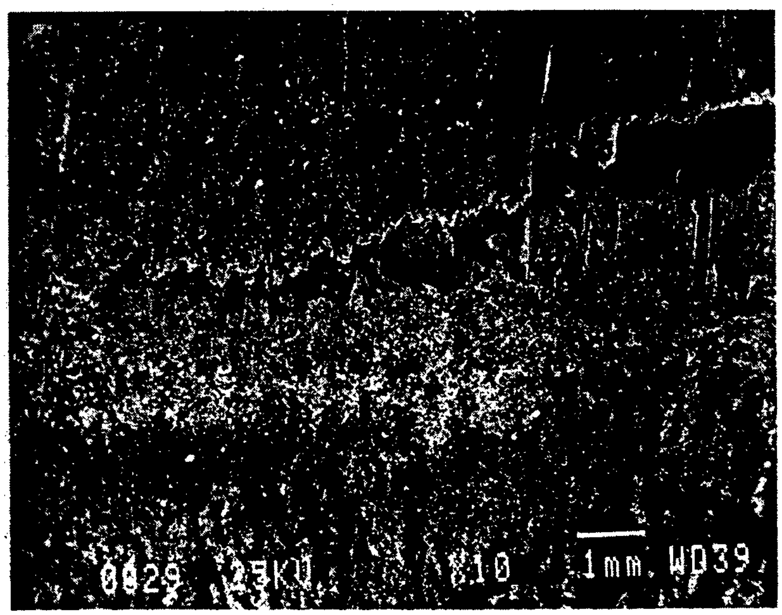


FIG. #9 **10X**

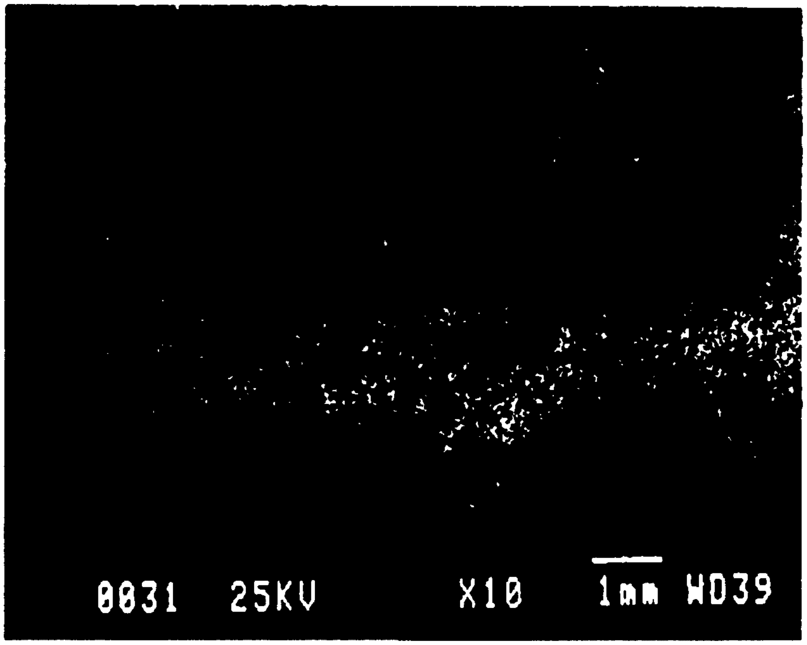


FIG. #9A **Si MAP** **10X**

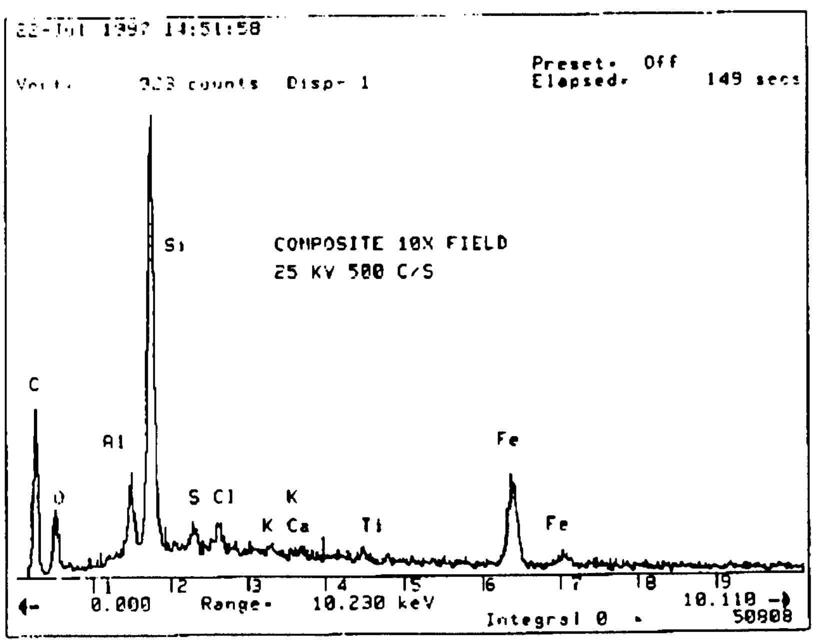
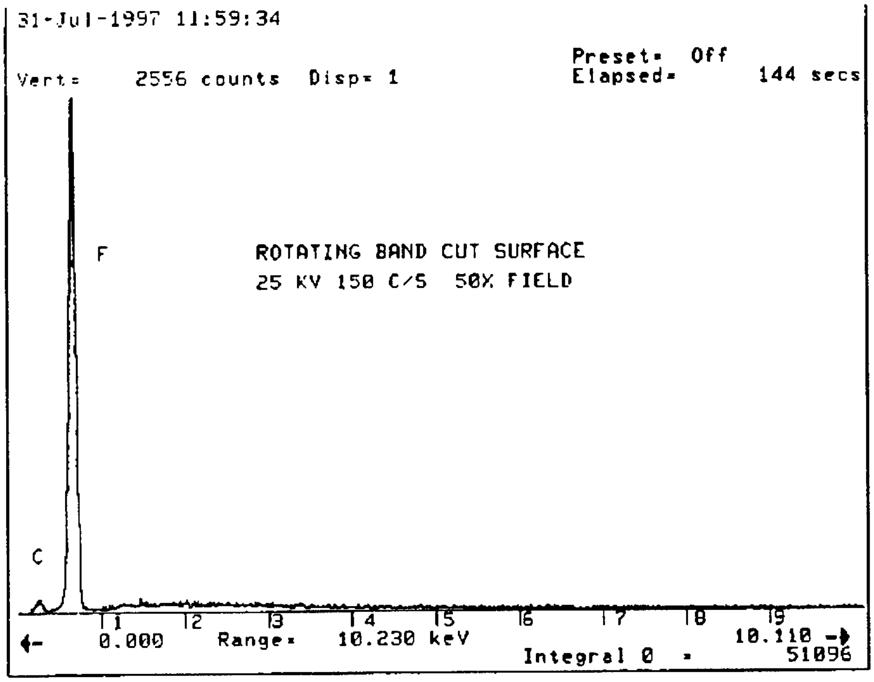


FIG. #9B **EDX**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Vert= 2556 counts Disp= 1
Preset= Off
Elapsed= 144 secs
F
ROTATING BAND CUT SURFACE
25 KV 150 C/S 50X FIELD
C
1
2
3
4
5
6
7
8
9
0.000 Range= 10.230 keV
10.110
Integral 0 = 51096

FIG. #10 **EDX**

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